# The preponderance of lithium-ion batteries for energy storage systems: a brief review

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**Abstract.** In view of the growing energy demand, energy storage systems are indispensable in most of the instances that compose and guide society. In this regard, lithium-ion batteries are one of the most significant forms to supply the energy demand of many applications that depend on the delivery of constant power over prolonged periods. They are a great alternative for small to large-scale applications. It is cognizable that they are electrochemical devices with high energy density and specific energy, and countless advantages for this purpose. Therefore, this paper is a brief literature review with the purpose of discussing and describing the prominence of these batteries in the context of energy storage. To this end, it is outlined from the introductory comments, a brief historical contextualization of the technology of lithium-ion battery, citing the discoveries that led to its recognition in the 2019 Nobel Prize in Chemistry, followed by a basic and general overview of its operating principle, moving on to a mention of its applications in everyday life, and finally addresses a preliminary perspective about what exists in the literature about the future of this technology, such as the so-called post-lithium-ion batteries, and its potential scientific and technological enhancement. From this, the conclusion of the literature review is elaborated given the constructed overview.

**Keywords.** Lithium-ion batteries, energy storage systems, electrochemical devices.

# 1. Introduction

The growth in energy demand constitutes one of the main particularities of mankind since the conception of technologies from modern science [15]. Thus, in the global context, this growth is due mainly to the potential improvement of living standards in developing countries, presenting essential aspects for the policy and energy planning of emerging economies. However, it is known that the energy sources most used for the production of electricity come from fossil and non-renewable sources, such as oil, coal, and natural gas [14].

Therefore, one of the prominent visions of the present concerns the alliance of energy demand with sustainable alternatives for energy production. In this context, energy storage systems present themselves as crucial ways to meet small and large-scale energy demands and to promote the use of renewable energy sources (RES) [7].

In this concern, batteries play an important role; this is evidenced by the fact that on a daily basis, batteries are used to supply the energy demand of many applications that depend on the delivery of constant power over extended periods, such as electric vehicles (EVs), photovoltaic (PV) systems and many electronic devices, including smartphones [10]. They are a long-established means of storing electricity in the form of chemical energy, they are classified as primary batteries and secondary or rechargeable batteries, which are the ones mostly used in large energy storage applications [8,9].

Furthermore, when it comes to batteries and their technologies, it is indispensable to mention the revolution promoted by lithium-ion batteries. This importance is ratified and emphasized by its highest recognition: The 2019 Nobel Prize in Chemistry is awarded to John B. Goodenough, M. Stanley Whittingham and Akira Yoshino for their contributions to the development of the lithium-ion battery[2]; this is the rechargeable battery that laid the foundation for wireless electronics such as cell phones and laptops, and according to the Royal Swedish Academy of Sciences [1,2]: "It also makes possible a world free of fossil fuels, as it is used for everything from powering electric cars to storing energy from renewable sources."

The ingenious use of lithium (Li) ions for battery applications has provided great guarantees and noteworthy features for this application: these batteries have high energy to weight ratio, i.e., high energy density and specific energy, high capacity, no memory effect, low self-discharge and long cycle life. [4,5,8,14], which is very suitable for the utilizations mentioned.

In light of this, the purpose of this paper is to demonstrate a brief literature review demonstrating the basic, yet indispensable, aspects of lithium-ion batteries and, contained in this approach, the preponderance of this technology for today's everyday life and the perspectives that permeate its future in the science and technology of energy storage systems. In order to highlight such prominence, the present literature review is organized into a brief historical background, working principle, technological applications, and future prospects concerning lithium-ion batteries.

# 2. Historical background

The history of batteries dates back to the late 19th century, when Italian scientist Alessandro Volta observed that when two different metal probes are placed in certain chemical solutions, the production of electricity occurs, this principle became known as the Volta battery [1,11,19]. Since then, numerous experiments and scientific advances have been made to improve the technologies for storing energy, as can be seen in Figure 1 well elucidated by [9].

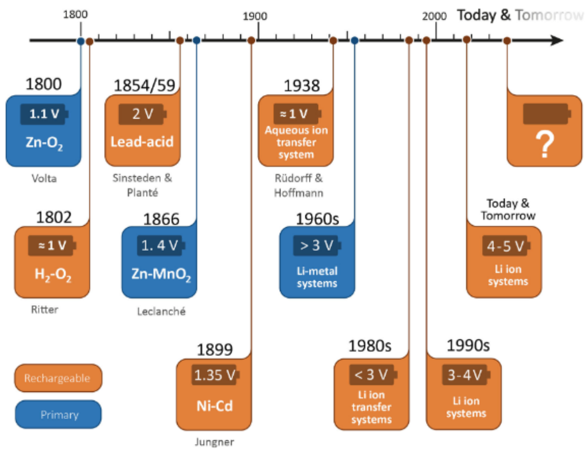


**Fig. 1** – The development of batteries from 1800 until today [9]

Hence, it is noticeable that the operating voltages have improved over time, and with it the life cycle and application possibilities in view of the life cycle have been improved. This in turn is due to improved physical and chemical structures, some batteries, such as the Ruben-Mallory (RM) battery, could be duly replaced by Li-ion batteries, as the previous ones were toxic and only had a lifetime of 2 years [9].

Besides that, it is well known that there are prominent types of electrochemical batteries today, for example, nickel-cadmium, lead-acid, metal-air batteries [4, 7,11]. Nevertheless, the critical insertion of lithium into batteries, however, came about when it was observed during the 20th century that the energy densities and capacities of the developed batteries were quite limited and would need better configurations [2].

Looking at the periodic table, summarized and cut appropriately in Figure 2, it is noticeable that the element lithium has atomic number 3 and is the lightest metal and coupled with its very low density of standard reduction potential (Li+/Li -3.05 V vs SHE), and this made it suitable for high density, high voltage battery cells, as mentioned in the scientific background of [1].


**Fig. 2** – Lithium element in the periodic table

Moreover, on the information from [1,2], it is known that the first studies on the electrochemistry of lithium occurred as early as 1913 by Gilbert N. Lewis, but the interest in lithium for battery applications became more evident in the 1960s and 1970s.

In face of the efforts to study lithium applied in batteries, it was observed that this kind of battery could be extremely reactive, precisely because of the electrochemistry of lithium, requiring non-aqueous electrolytes [1,6,15]. Allied to observations like this, lithium ions emerged as a plausible choice for the composition of secondary batteries as electrolytes, respecting their stoichiometry, during a conference held in Belgirate, Italy, in 1972 [1,2].

With the insertion of lithium, an indispensable principle provided by it is intercalation, essential for designing charge and discharge in the battery and consequently leading to the development of the so-called rechargeable (or secondary) batteries [2,6]. In 1973, the Nobel laureate Whittingham to explore electrochemical intercalation in lithium-based batteries, proposed such materials as electrodes in batteries, thus, a working presenting the rechargeable battery was posteriorly demonstrated in 1976 [2,9].

Furthermore, during the studies of lithium batteries, numerous paradigm shifts had to be made to ensure the safe use of these batteries and thus their commercialization. For example, despite offering advantages in specific energy, the use of lithium metal anodes had to be replaced commercially due to their limited life cycle, the lithium electrode when interacting with the electrolyte leading to its drying out, and the cell requiring exorbitant charging periods, in the range of several hours [6,9].

With the demands and needs for improvements, the contributions of the other Nobelist scientists have been invaluable in securing lithium-ion battery-powered technologies: Between 1979 and 1980, Goodenough and his collaborators at Oxford University in the UK discovered a new class of cathode materials, the layered transition metal oxides, with the intent of acquiring a superior electromotive force cell in combination with anodes of higher potential than lithium metal. They discovered that $Li_xCoO_2$ could serve as a cathode material and this allowed the use of anode materials with higher potentials than lithium metal, leading to the search for suitable carbonaceous materials [1,9]. In 1985, the group led by Akira Yoshino at Asahi Kasei Corporation in Japan identified that certain grades of petroleum coke were stable under the required electrochemical conditions [1].

These fundamental advances and discoveries became commercially plausible and successful in 1991, when Sony Corporation's commercial lithium battery introduced a high energy (80 Wh/kg) and high voltage battery of, approximately 3.7 V, a cell based on coke as the anode material, a non-aqueous electrolyte and $LiCoO_2$ as the cathode material, and was thus the primary materialization of laureate studies on lithium-ion batteries [9].

Whereas, it is explicit how great and peremptory these studies are for energy storage technologies, they still have enabled current and ongoing studies to improve lithium-ion batteries to find higher specific energy and power density, with the development of advanced components considering the active (anode, cathode) and inactive materials (electrolyte, separator, binder, conductive additive, etc.) as well as improvements in manufacturing and engineering [8,9].

# 3. Working principle

As mentioned, lithium-ion batteries are electrochemical devices, i.e., they convert chemical energy to electrical energy during discharging, and the opposite process occurs during charging [17], through an oxidation-reduction chemical reaction. According to [18], lithium-ion refers to a class of rechargeable cells that use lithium intercalation reactions in both electrodes [1,15]; in this context, lithium ions travel between the two electrodes in a so-called rocking chair framework.

In a more detailed view, as shown in Figure 3, Li-ion cells are composed basically of a negative electrode (anode), a positive electrode (cathode), an electrolyte, a polymeric separator and two current collectors. During discharge, lithium ions move towards the cathode through the electrolyte; and during charge, they move in the direction of the anode, this means that electrons move from positive to negative electrode through the external circuit. Therefore, the battery delivers a current, feeding the external circuit electrical energy acquired through the conversion of stored internal chemical energy present in the battery [16]. Moreover, whenever a charger provides electrical energy to the battery cell, that energy is stored as electrochemical potential energy.

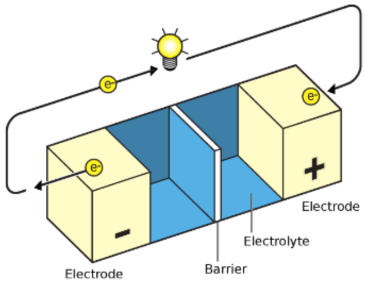


**Fig. 3 –** Working Principle of a Li-ion cell [1]

# 4. Li-ion battery applications

The use of Li-ion batteries is already well established in various technological applications, among which are for portable electronic devices to electric vehicles: hybrid (HEV), plug-in (PHEV), or fully electric vehicles (BEV), and stationary energy storage, such as for RES, like photovoltaic systems (PVS) and wind turbines [9,15]. In this aspect is certain to infer that these batteries also have a vital role in transportation and micropower generation utilization [3,8].

In addition, with the improvements of these batteries, [15] shows the increase of their use in predominantly industrial applications along with the others mentioned above, also including power tools, gardening tools, e-bikes, medical devices and related devices, as shown in Figure 4.

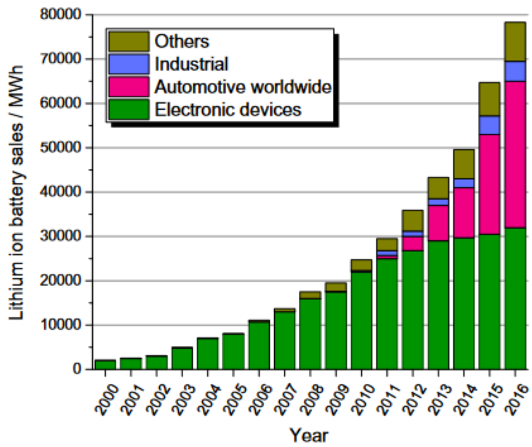


**Fig. 4 –** Lithium-ion battery sales worldwide from 2000 to 2016 (cell level) [15] with the data provided by [20]

# 5. The future of Li-ion batteries

Li-ion batteries are the batteries with the highest energy density today, which means they offer the greatest development potential for future application in a wide variety of energy storage systems. However, it is necessary to analyze that the demand for this technology is out of balance with the current generation of lithium devices, in this sense it emphasizes the indispensability of fundamental research in materials science for electrodes and electrolytes [12]. As well clarified by Goodenough in [13], one of the main challenges of today refers to the design of an electrochemical technology that is capable of reliably performing the task of electrical energy storage as well as recovery at a rate and competitive cost with the performances well-established fossil fuel technologies.

Similarly, future battery-energy storage technologies are expected to offer improved energy and power densities, although in practice the gains in reliability, longevity, cycle life expectation and cost may be more significant than the energy increases [9]. Therefore, it is essential that studies aim to reduce the capital cost of lithium-ion batteries by optimizing auxiliary components such as packaging and overload protection circuits [12].

Furthermore, it is well known that the specificities and hazardousness level of Li-ion batteries require a sophisticated management system (BMS) [7,18], a fact that in itself makes a demand for potential improvements and enhancements in current technologies.

In this perspective, so-called "post-lithium-ion batteries" have currently been developed, which are electrochemical systems whose specific energy is significantly higher than the specific energy of modern lithium-ion batteries, including battery systems, their projected cost will be significantly lower or other key features will be significantly higher. For example, to this category belongs: lithium-oxygen batteries, sodium-ion batteries, and lithium-sulfur batteries [5].

These systems are being actively studied and are not currently ready for industrial production. According to [6], in general, a realistic estimation and comparison of the specific energy and energy density and other performance parameters of different post-lithium-ion technologies to state-of-the-art lithium-ion batteries will only be possible if consistent and standardized cell sets and measurement protocols are used and if authors consistently publish all important parameters that allow a fair comparison.

# 6. Conclusion

In view of the literature reviewed, it is cognizant that lithium-ion batteries have important performance in energy storage systems and this fact is clearly observable in everyday technological applications. Moreover, it is indispensable to mention how unprecedented this technology is for studies in the physical sciences, chemistry and engineering, representing a historical milestone.

Although it is a mature technology, it is determining for the improvement of batteries energy storage that continuous studies must be made to enhance the energy and capacity specificities of current Li-ion batteries. As with any scientific endeavor, improvements must be promoted to establish and enhance society's quality of life, and with the post-lithium-ion batteries and their future advanced versions, it is hoped that greater demands can be met by increasing the use of renewable energy sources, in order to guarantee long and sustainable stocks for all generations that will enjoy the technologies of energy storage systems.

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